Preparing for the San Andreas Fault Observatory at Depth: Results from Site Characterization Studies and the SAFOD Pilot Hole

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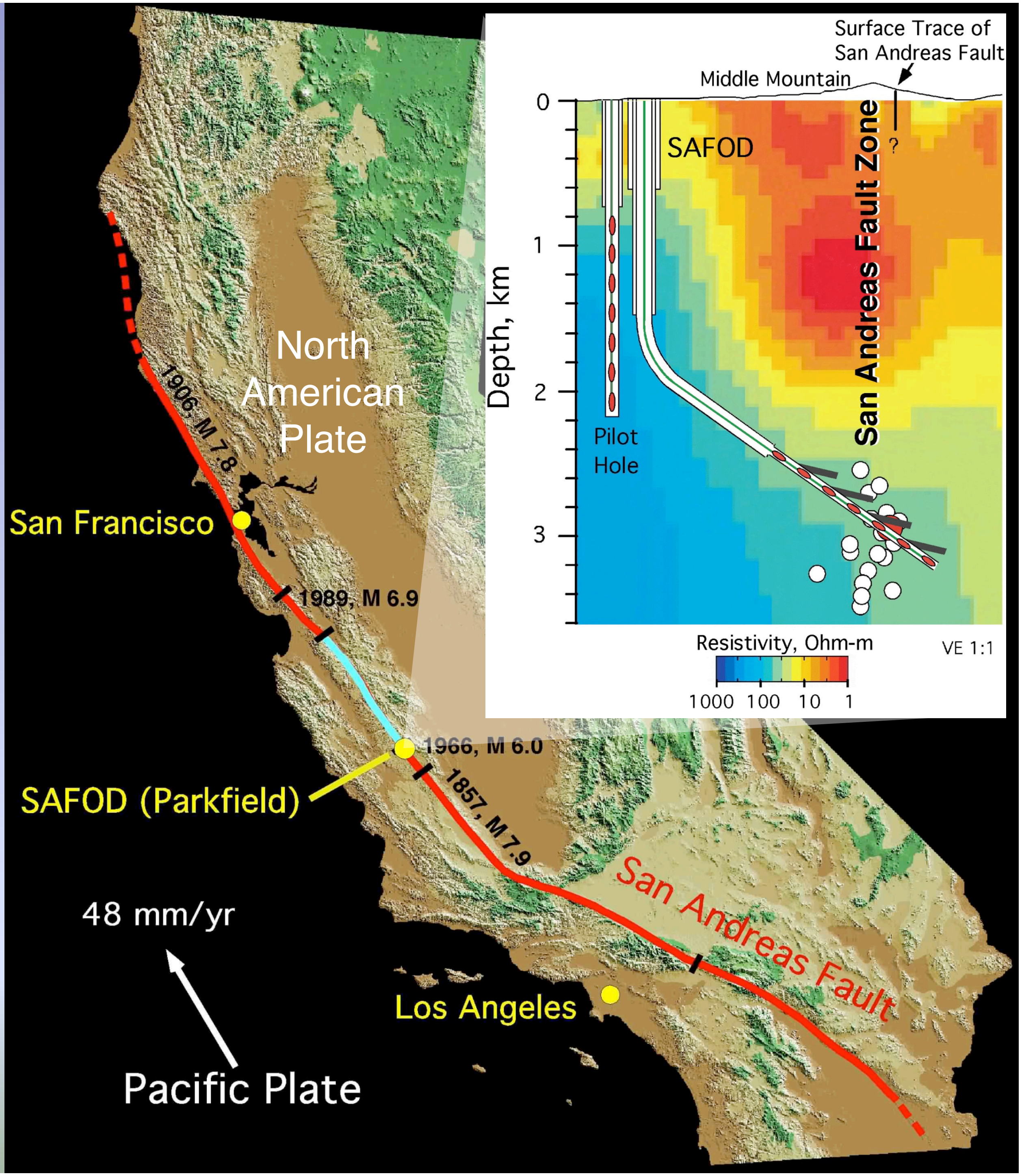
San Andreas Fault Observatory at Depth (SAFOD)

The central scientific objective of SAFOD is to directly measure the physical and chemical processes that control deformation and earthquake generation within an active plate-bounding fault zone.



EARTHSCOPE--A New View into the Earth

SAFOD -- A borehole observatory across the San Andreas Fault to directly measure the physical conditions under which earthquakes occur

Plate Boundary Observatory -- A fixed array of GPS receivers and borehole strainmeters to measure real-time deformation on a plate-boundary scale

USArray -- A continental-scale seismic array to provide a coherent 3-D image of the lithosphere and deeper Earth

San Andreas Fault Observatory at Depth: Project Overview and Science Goals

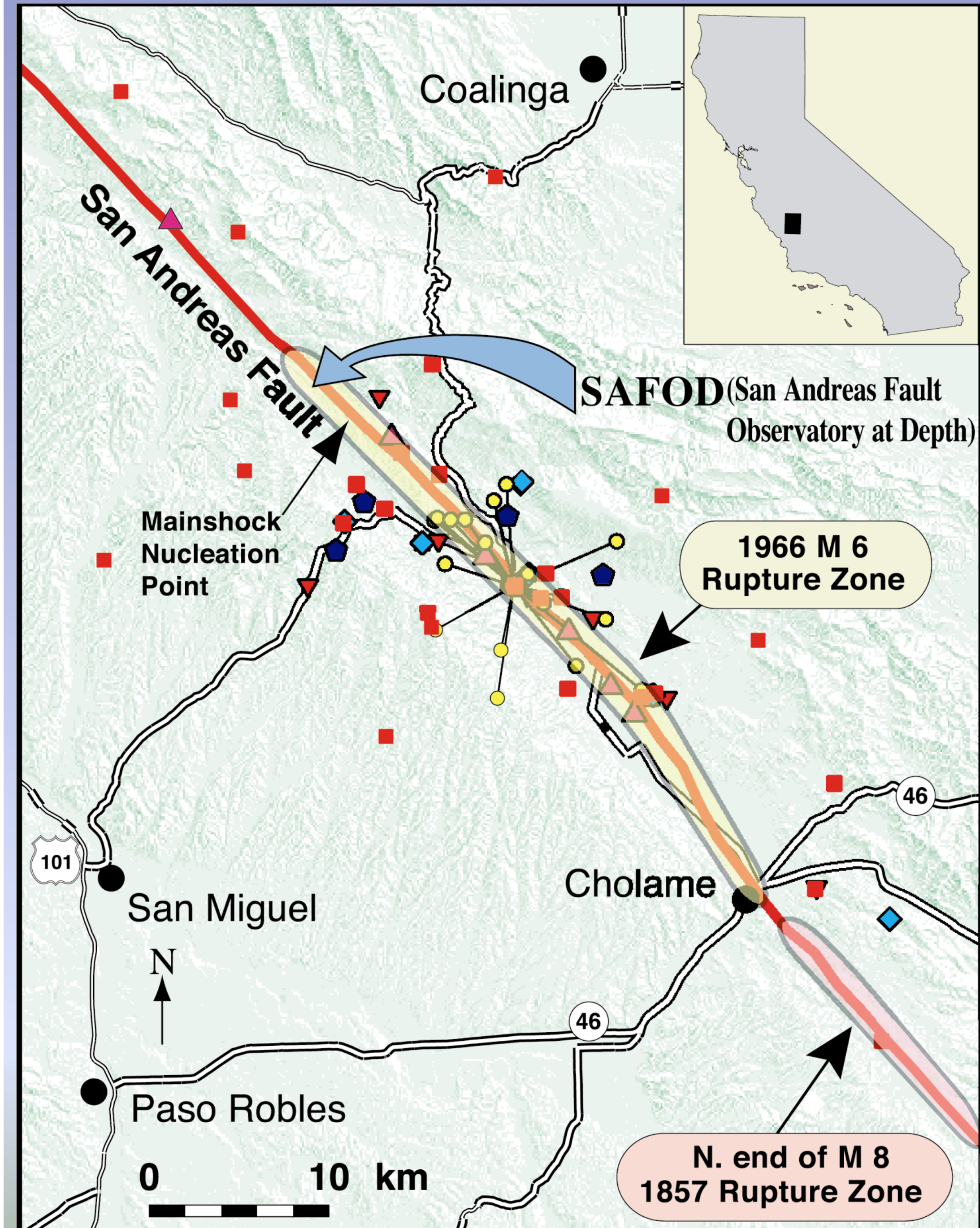
Test fundamental theories of earthquake mechanics:

- Determine structure and composition of the fault zone.
- Measure stress, permeability and pore pressure conditions in situ (fault zone and country rock).
- Determine frictional behavior, physical properties and chemical processes controlling faulting through laboratory analyses of fault rocks and fluids.

Establish a long-term observatory in the fault zone:

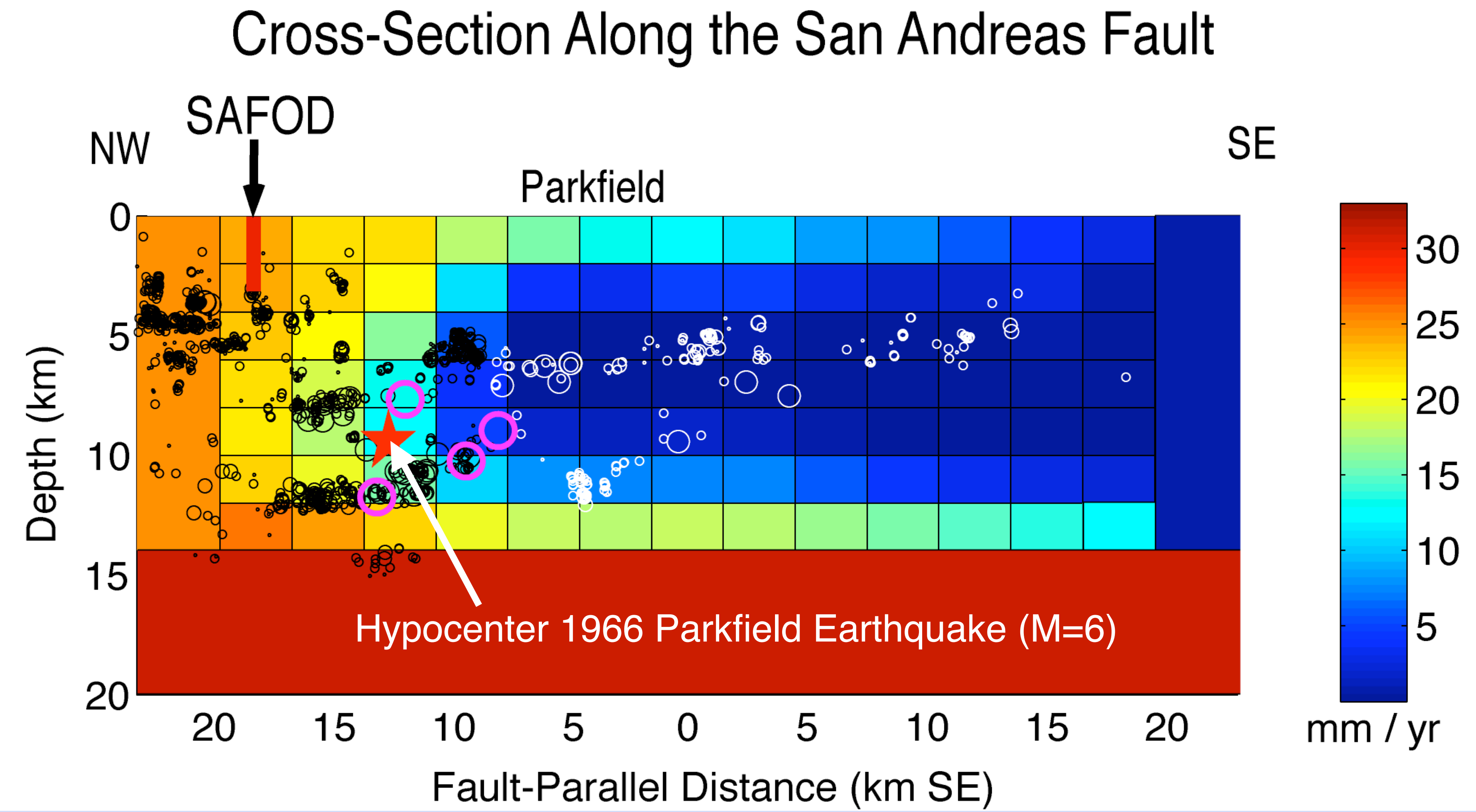
- Characterize 3-D volume of crust containing the fault.
- Monitor strain, pore pressure and temperature during the cycle of repeating microearthquakes.
- Observe earthquake nucleation and rupture processes in the near field.


N
San Andreas fault
SAFOD
drill site



SAFOD Location Takes Advantage of Knowledge Gained from The Parkfield Earthquake Experiment and the extensive network of monitoring instruments

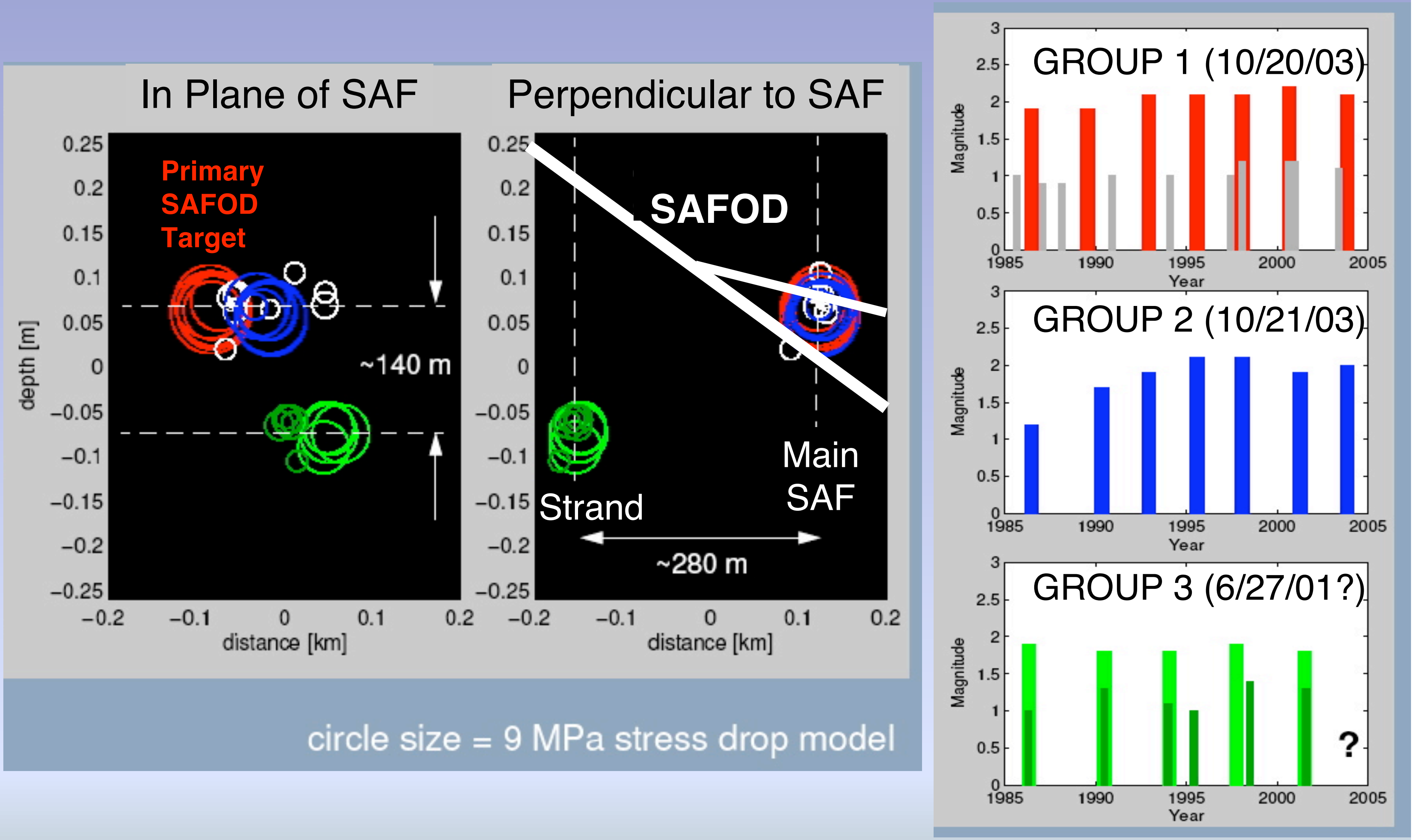
- Surface Seismometers
- Accelerometer Arrays
- Borehole Seismometers
- Borehole Strainmeters
- Creepmeters
- Water Wells
- GSP (including 1 Hz)



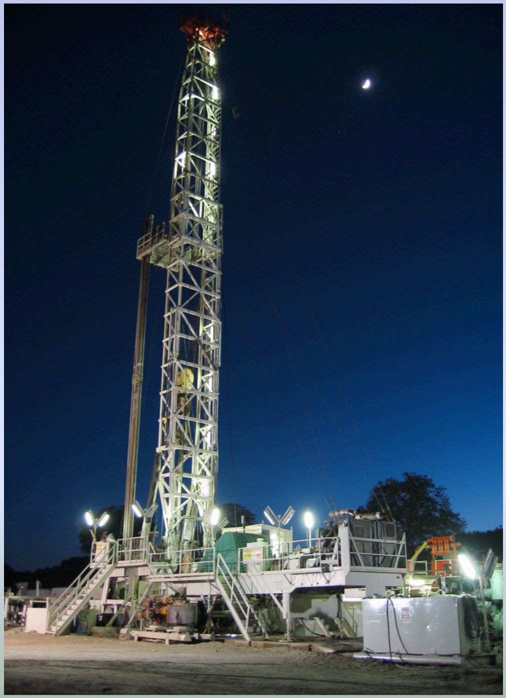
Slip rate inferred from geodetic measurements 1966-1991 (Jessica Murray et al. 2001)

Microseismicity 1984 - 1999, up to M 5 (Feliz Waldhauser & Bill Ellsworth)

Relative Locations of SAFOD Target Earthquakes (Repeaters)



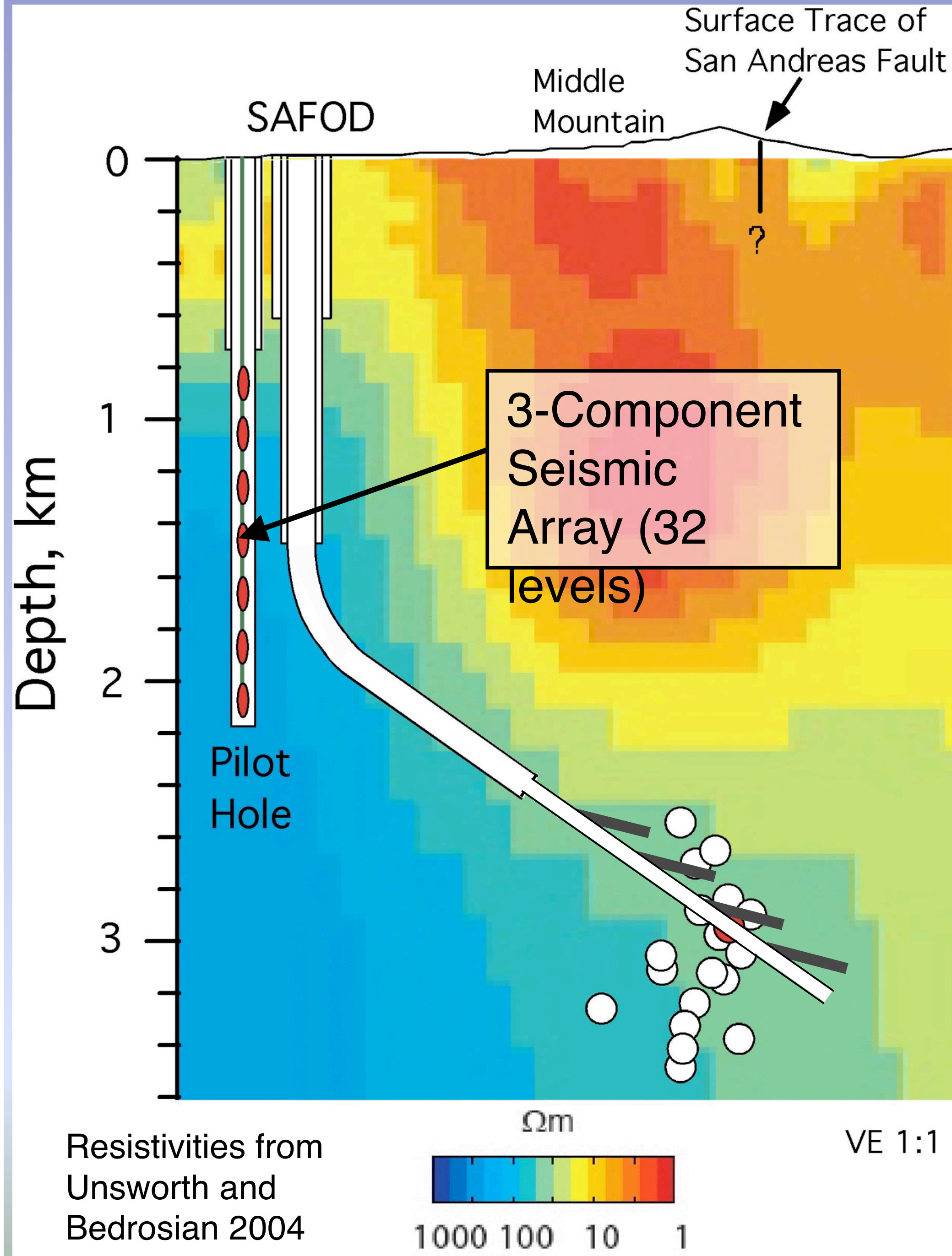
Felix Waldhauser 2004 (see also Nadeau et al., 2004)



Pre-SAFOD Activities

- ✓ Surface seismic array deployments (permanent & temporary, including 70-station PASO array 2000-02)
- ✓ High-resolution seismic reflection & refraction surveys through drill site and across SAF (1998, 2002, 2003)
- ✓ Magnetotelluric profiling
- ✓ Geologic Mapping
- ✓ Fault zone guided waves
- ✓ Gravity & magnetic surveys
- ✓ Fluid geochemistry

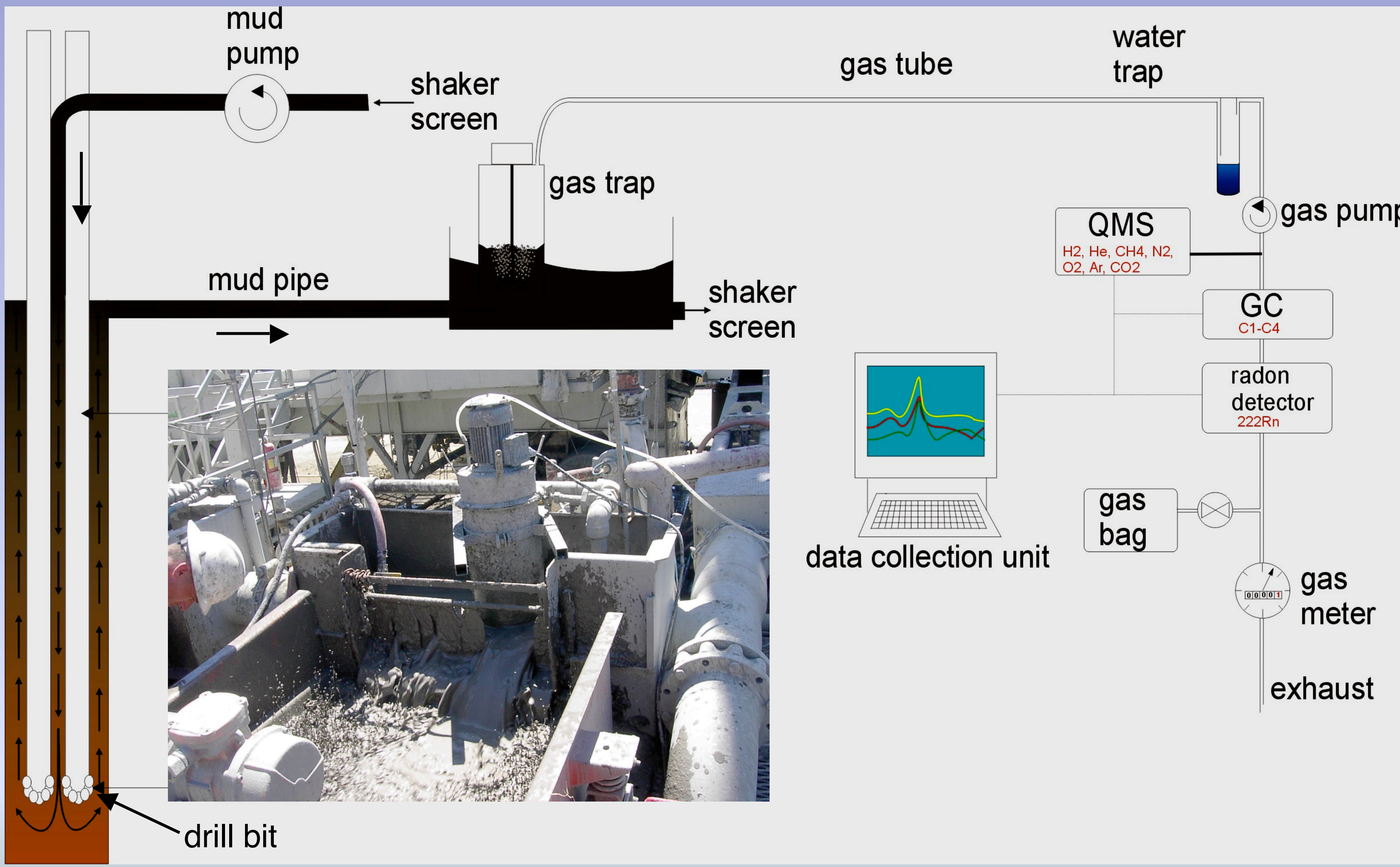
- ✓ Environmental assessment & permitting (completed)
- ✓ Geophysical Field Camp (Duke Univ.)
- ✓ Pilot hole drilled to 2.2 km at SAFOD site and instrumented with 32-level seismic array (summer 2002).
- ✓ Microearthquake relocations and seismic tomography (using data from surface and pilot-hole arrays)
- ✓ *Special issue of Geophysical Research Letters on site characterization and pilot hole results (2004, 20 papers).*



Pilot Hole Accomplishments

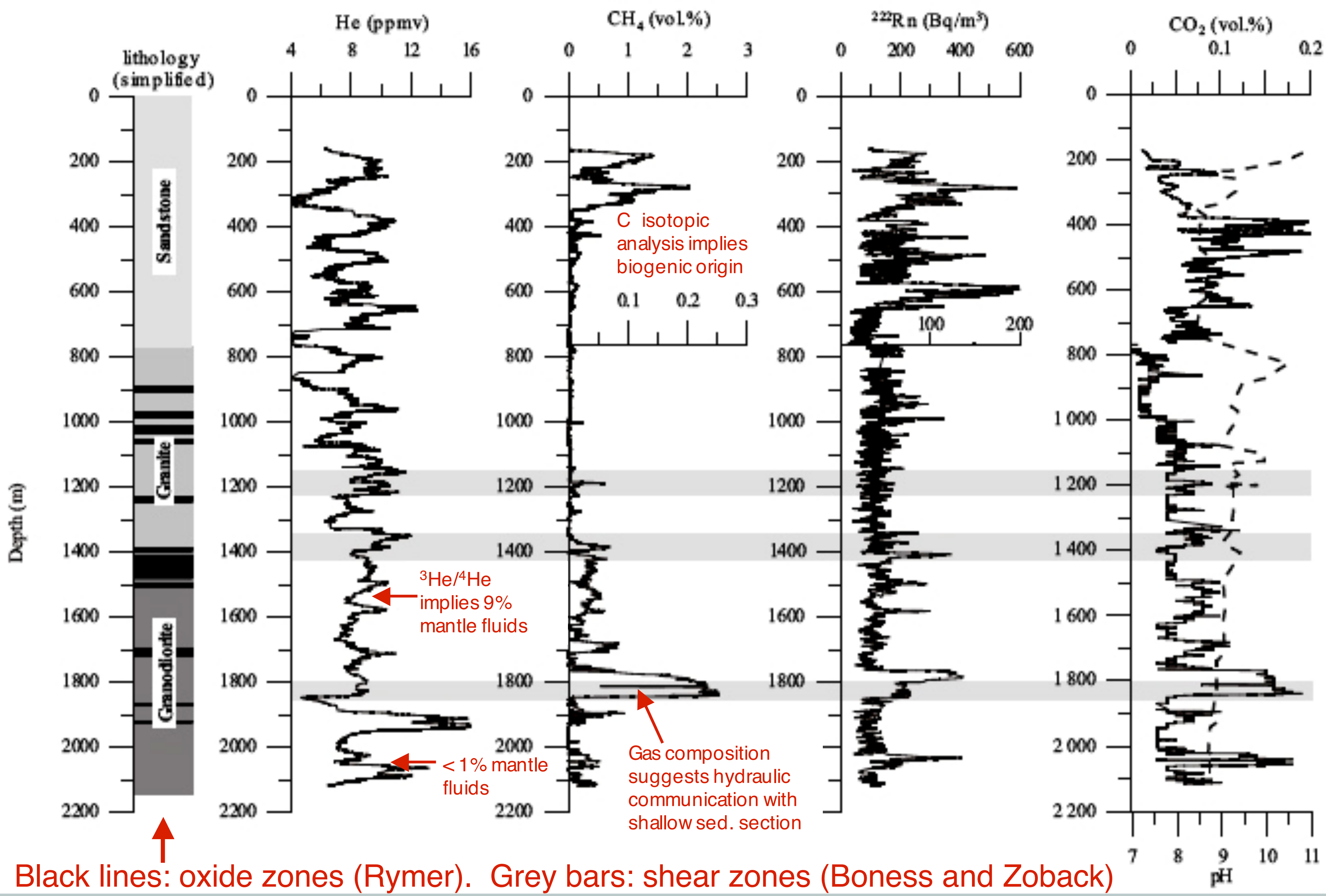
- Validated pre-drilling structural model (granite at 768 m) and provided technical information critical for SAFOD drilling plan.
- Measured stresses driving motion on SAF and confirmed the absence of frictionally generated heat on the fault.
- Provided background information on shear zones, fluid-rock interactions, thermal/uplift history and physical properties adjacent to SAF.
- Pilot hole seismic array helped refine locations of SAFOD target earthquakes and image secondary faults between drill site and SAF (as well as imaging the SAF itself).
- Providing test well for seismic, pressure and strain monitoring instruments to be used in SAFOD.

Real-Time Mud Gas Collecting and Analysis System



from Joerg Erzinger

Pilot Hole: Real-Time Mud Gas Logging Results



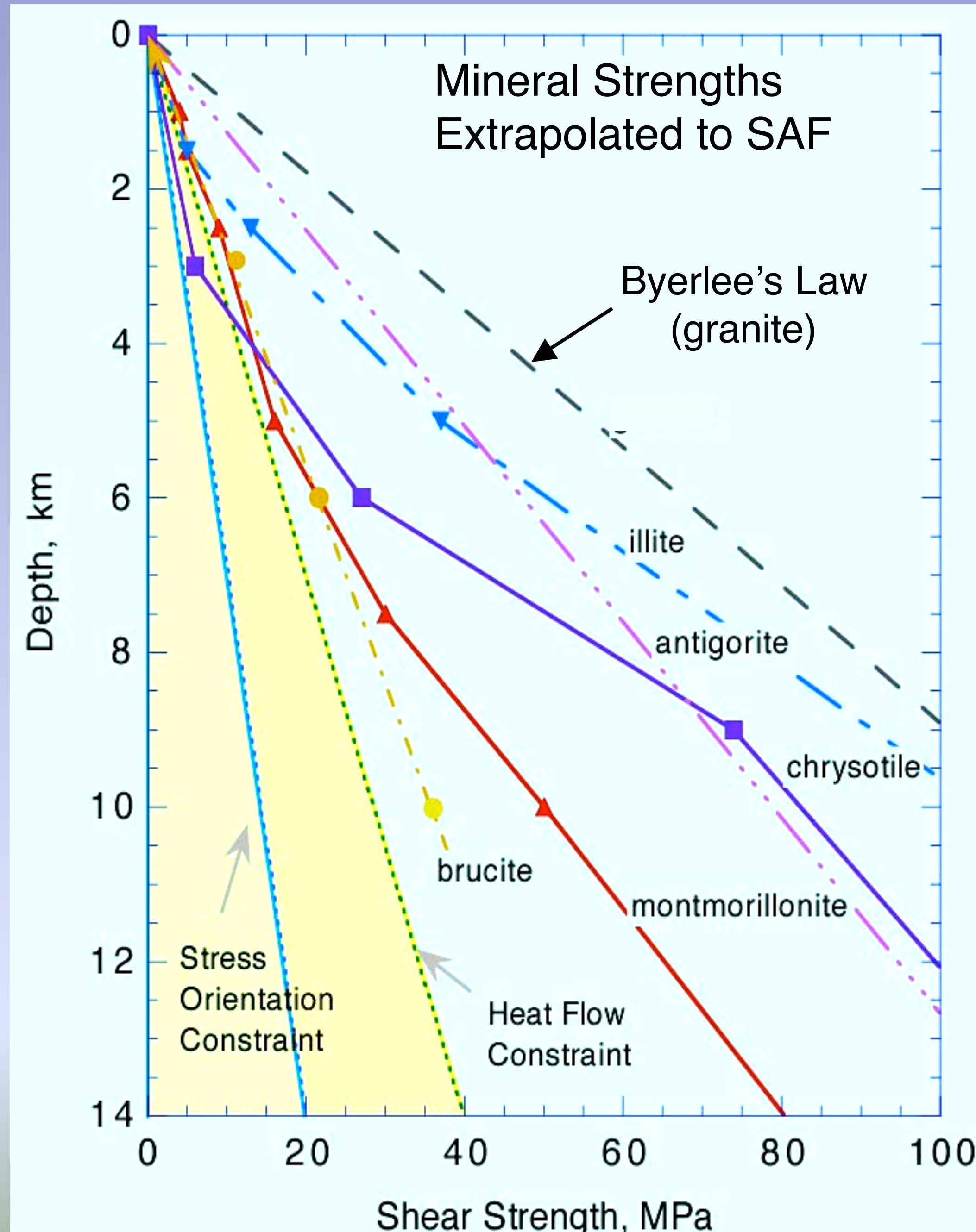
Black lines: oxide zones (Rymer). Grey bars: shear zones (Boness and Zoback)

Erzinger et al. 2004

Collecting Drill Cuttings from the Pilot Hole

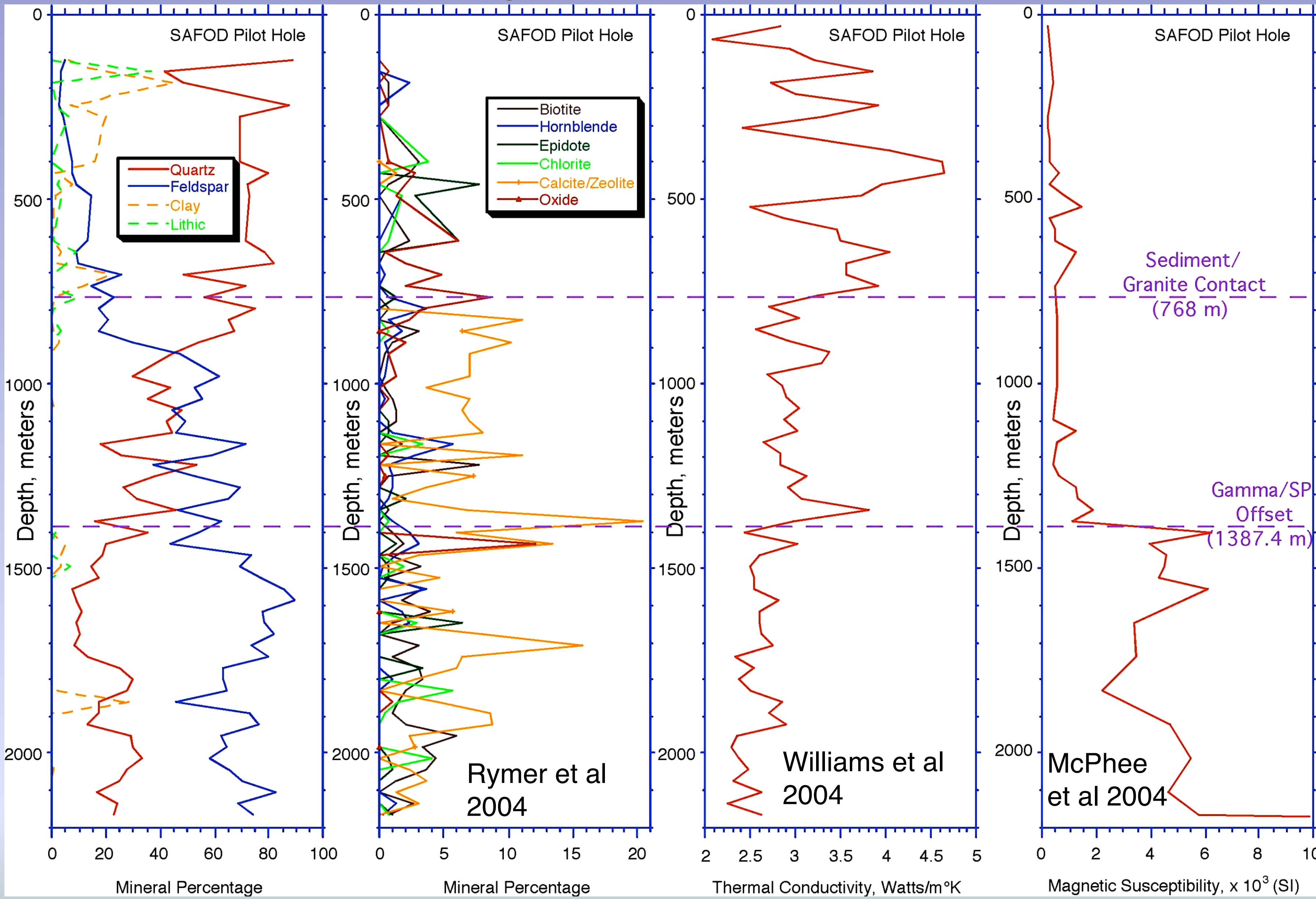
What are the mineralogies and frictional properties of minerals within the fault?

- Lab measurements show candidate weak minerals strengthen with increasing P & T.
- Due to loss of interlayer/surface water and phase transformations.
- Extrapolation to seismogenic depths shows weak minerals alone unlikely to satisfy heat flow or stress orientation constraint.



Morrow et al. 1992;
Moore et al.1997, 2001

Comprehensive Cuttings Analyses from SAFOD Pilot Hole

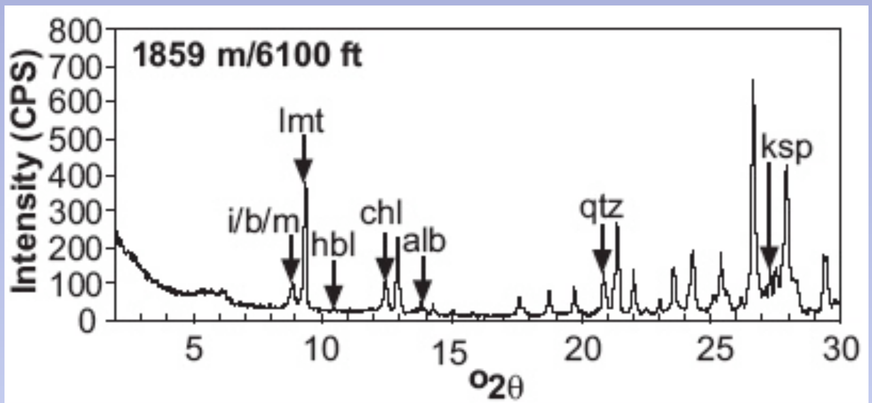


Detailed Cuttings Analysis: fine-scale mineralogy, fission-track and U-series dating, fluid inclusion geochemistry, alteration mineralogy (XRD, phylosilicates), radiogenic heat production

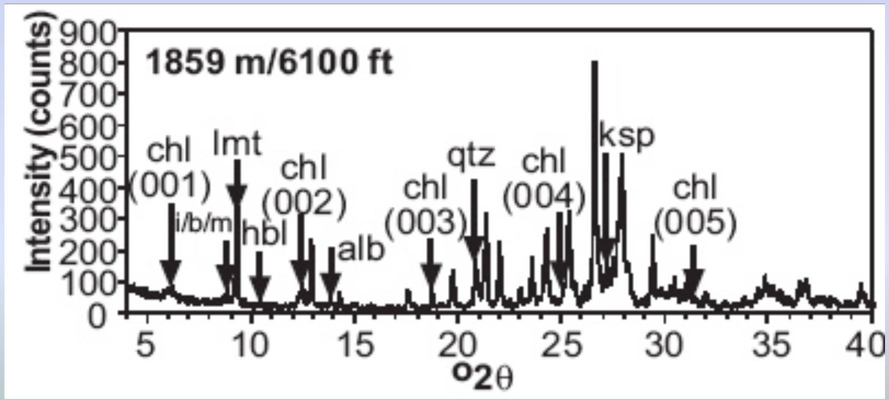
Phylosilicate Mineralogy from SAFOD Pilot Hole (Solum and van der Pluijm 2004)

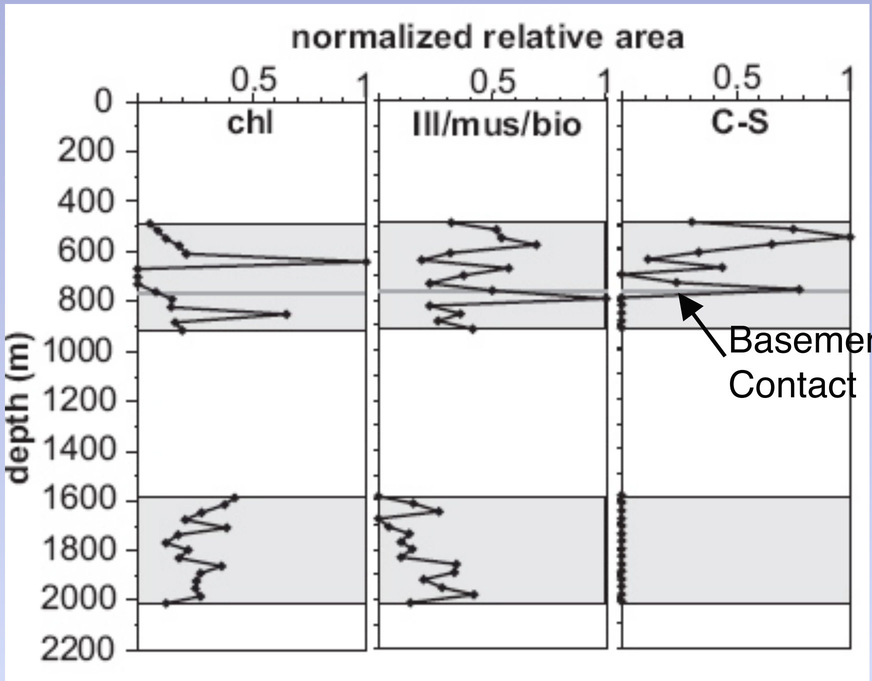
- Establish reference section for phylosilicate mineralogy across SAF with SAFOD
- Compare with phyl. mineralogy along exhumed ancestral SAF (Punchbowl Fault)

X-Ray Powder Pattern, for bulk mineralogy



Clay-sized fraction, for chlorite composition



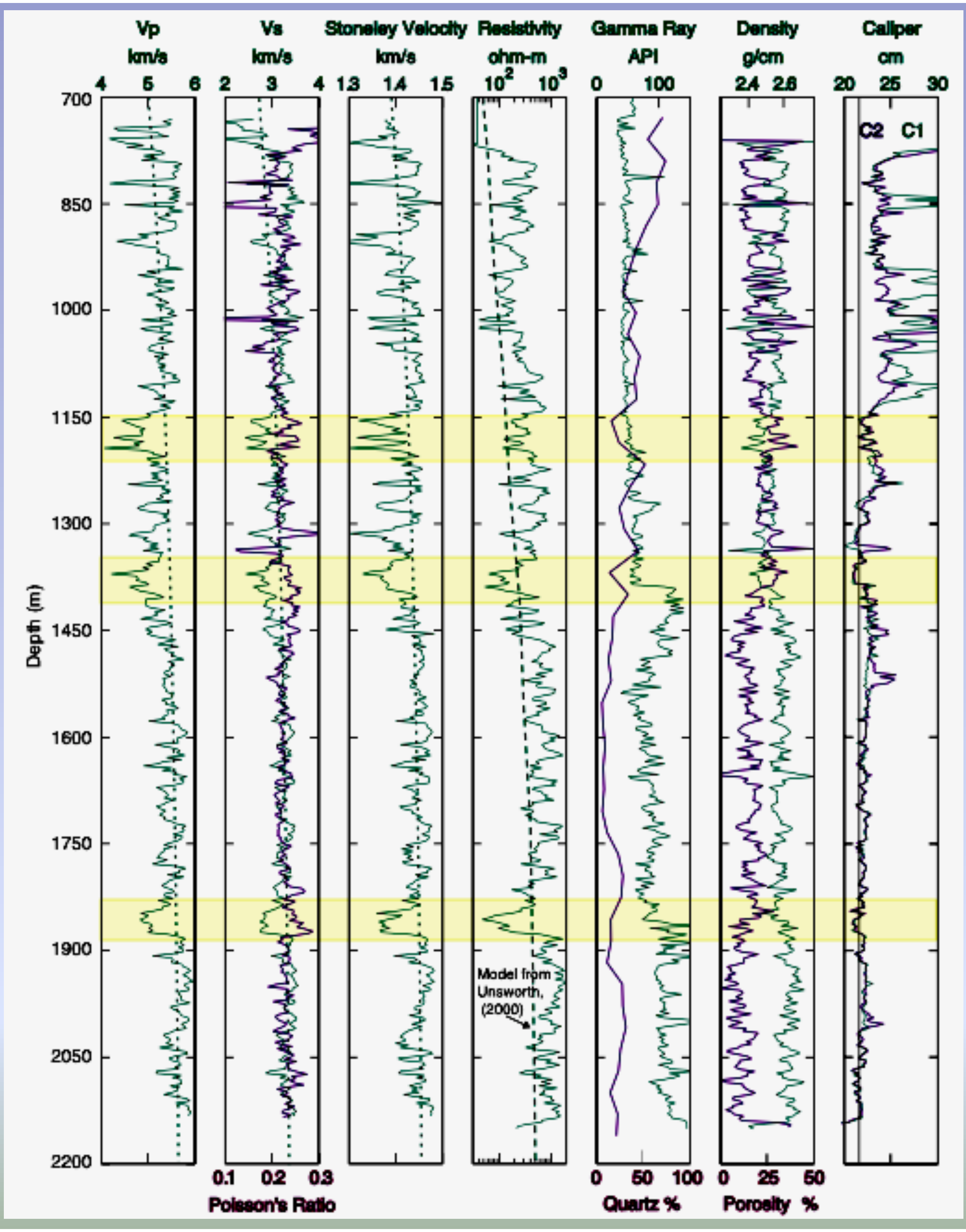


Generally more chlorite in granite basement than sediments

Higher concentration of mixed layer (chlorite-smectite) minerals in sediments, due to shallow alteration

Comprehensive Wireline Logging Program for Physical Properties and Geologic Structure

Pilot Hole Wireline Geophysical Logs Show Variations in Physical Properties with Depth



Shear Zones

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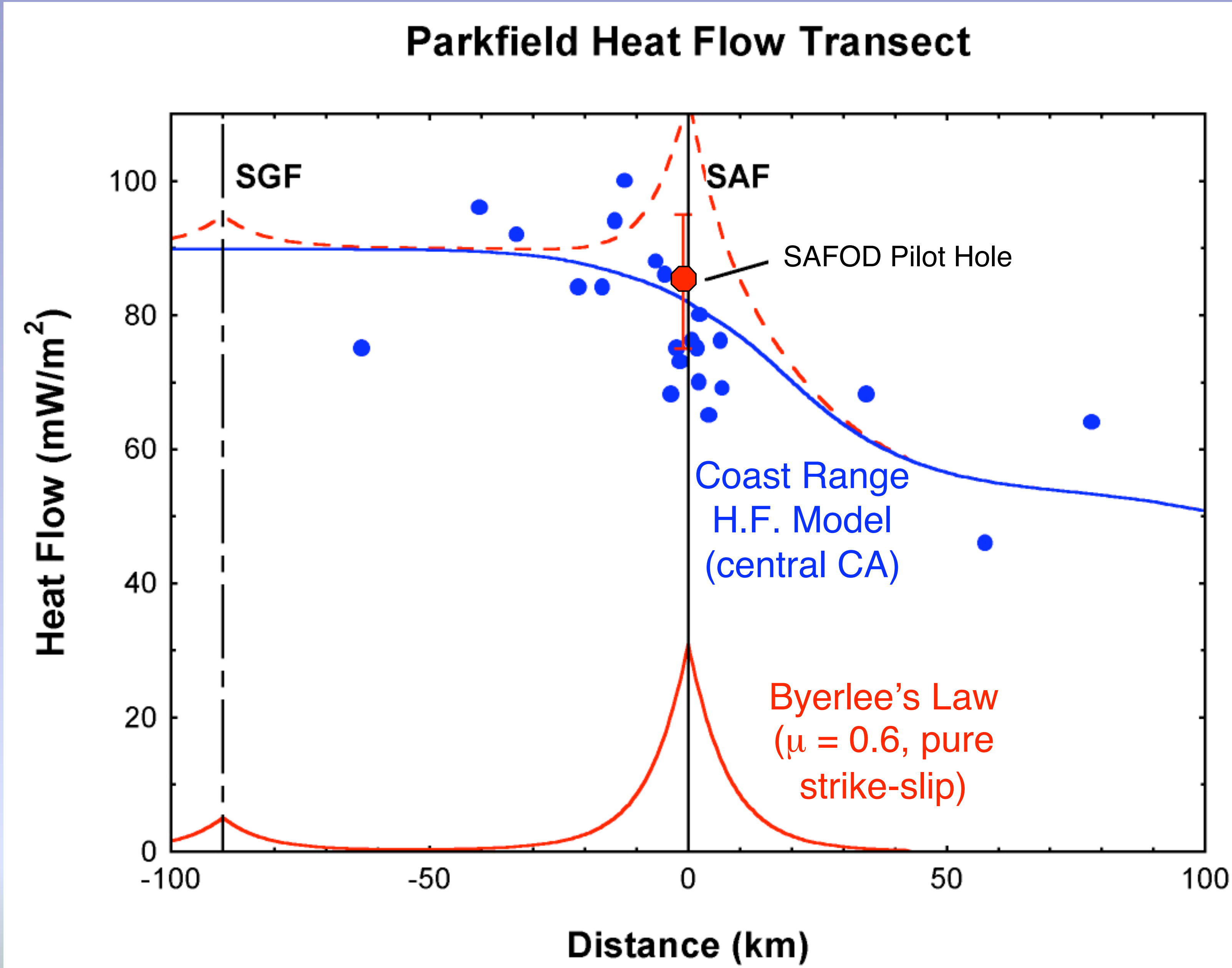
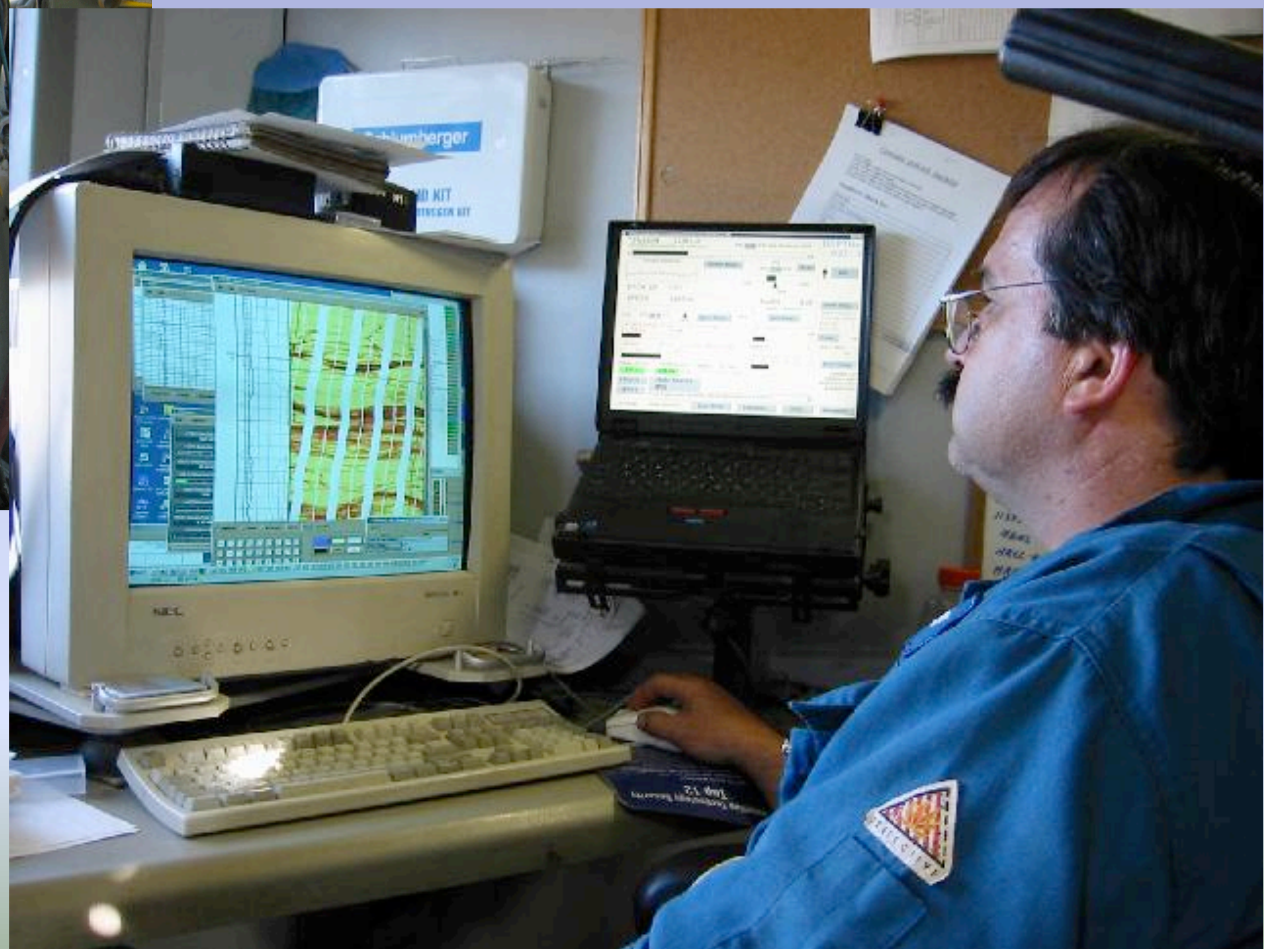
Boness and Zoback 2004

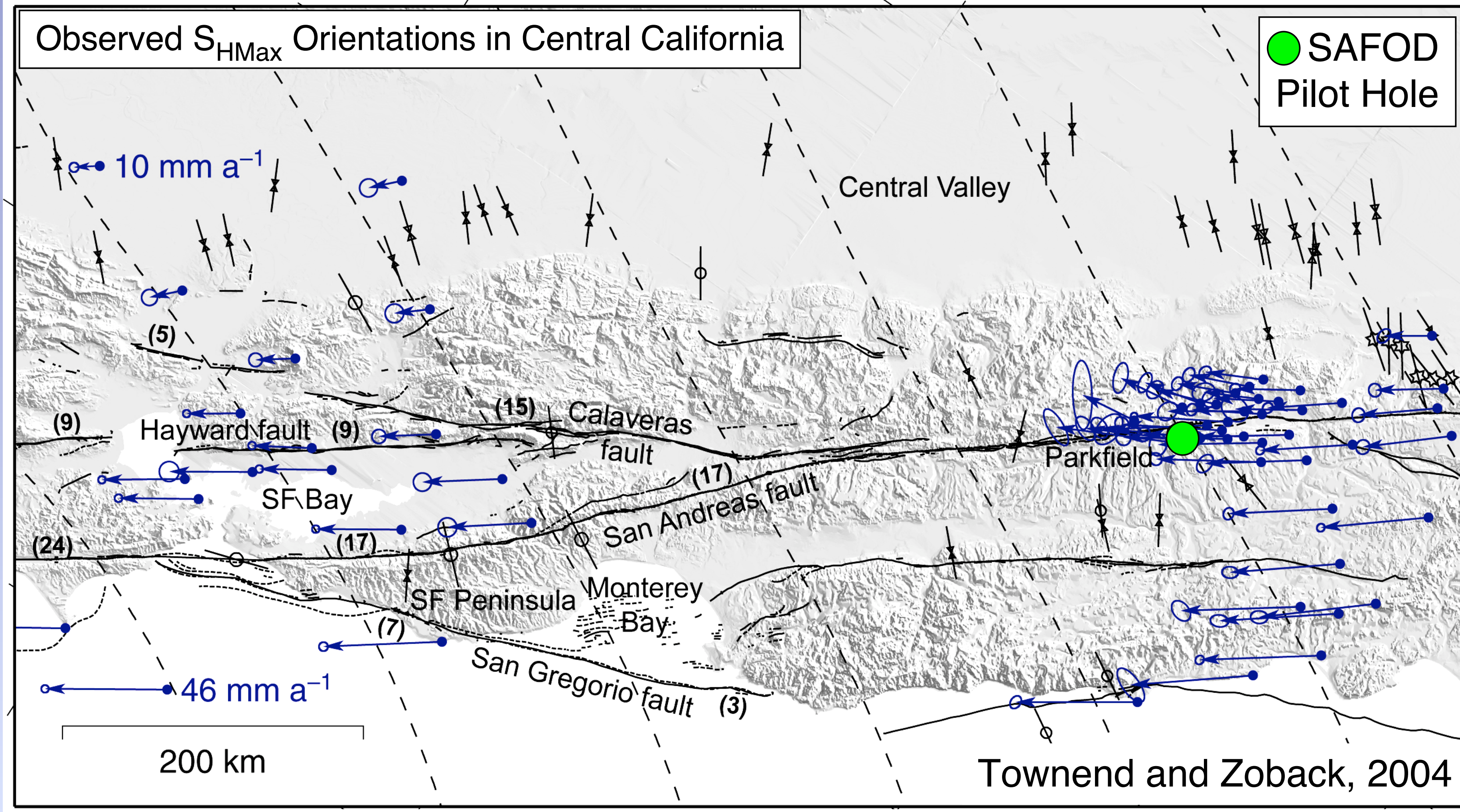


Williams et al 2004

Electrical and Ultrasonic Image Logging to Determine Stress State and Fracture Geometry

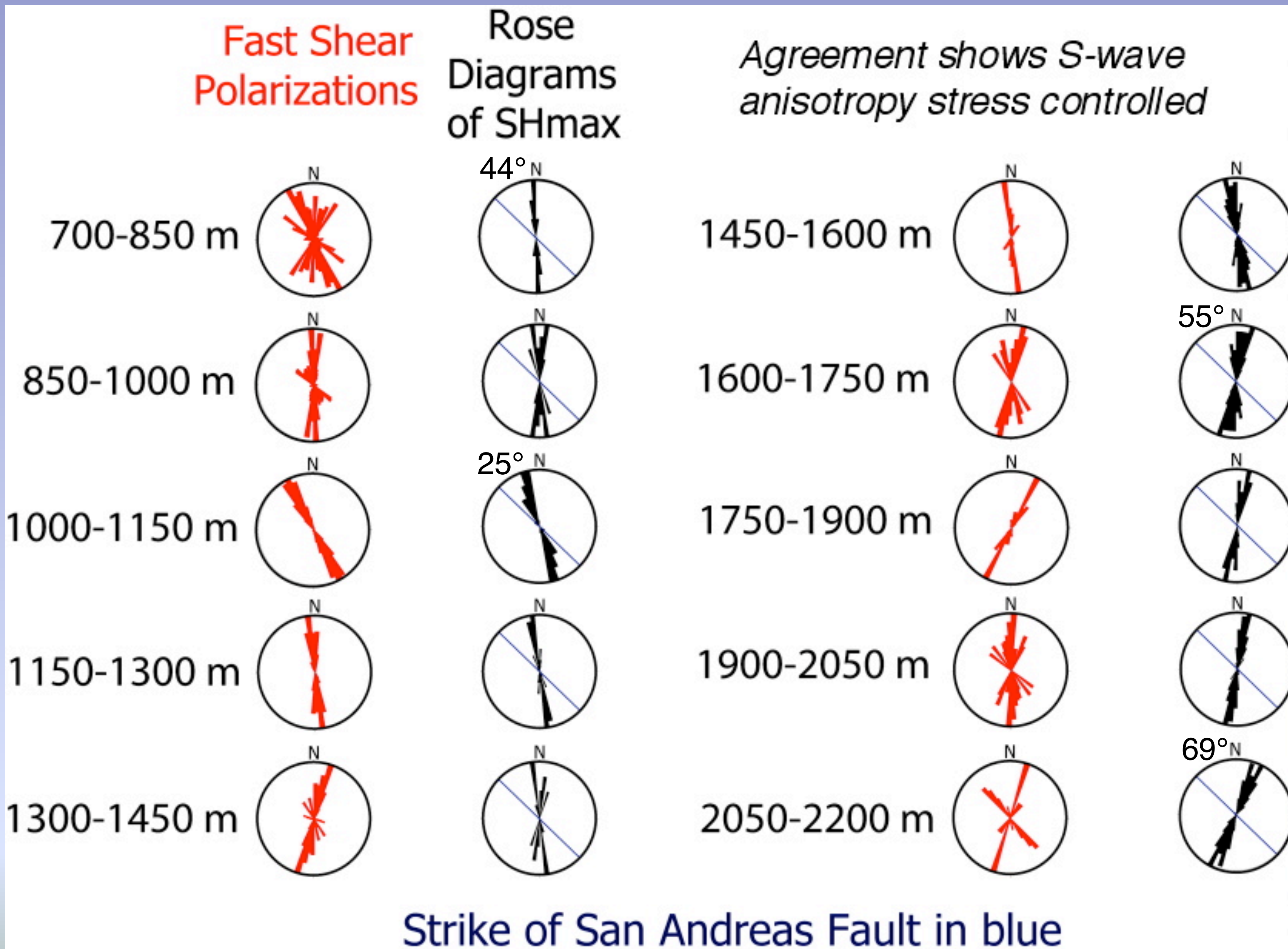


"Fault-Normal" Compression Indicates a Weak SAF



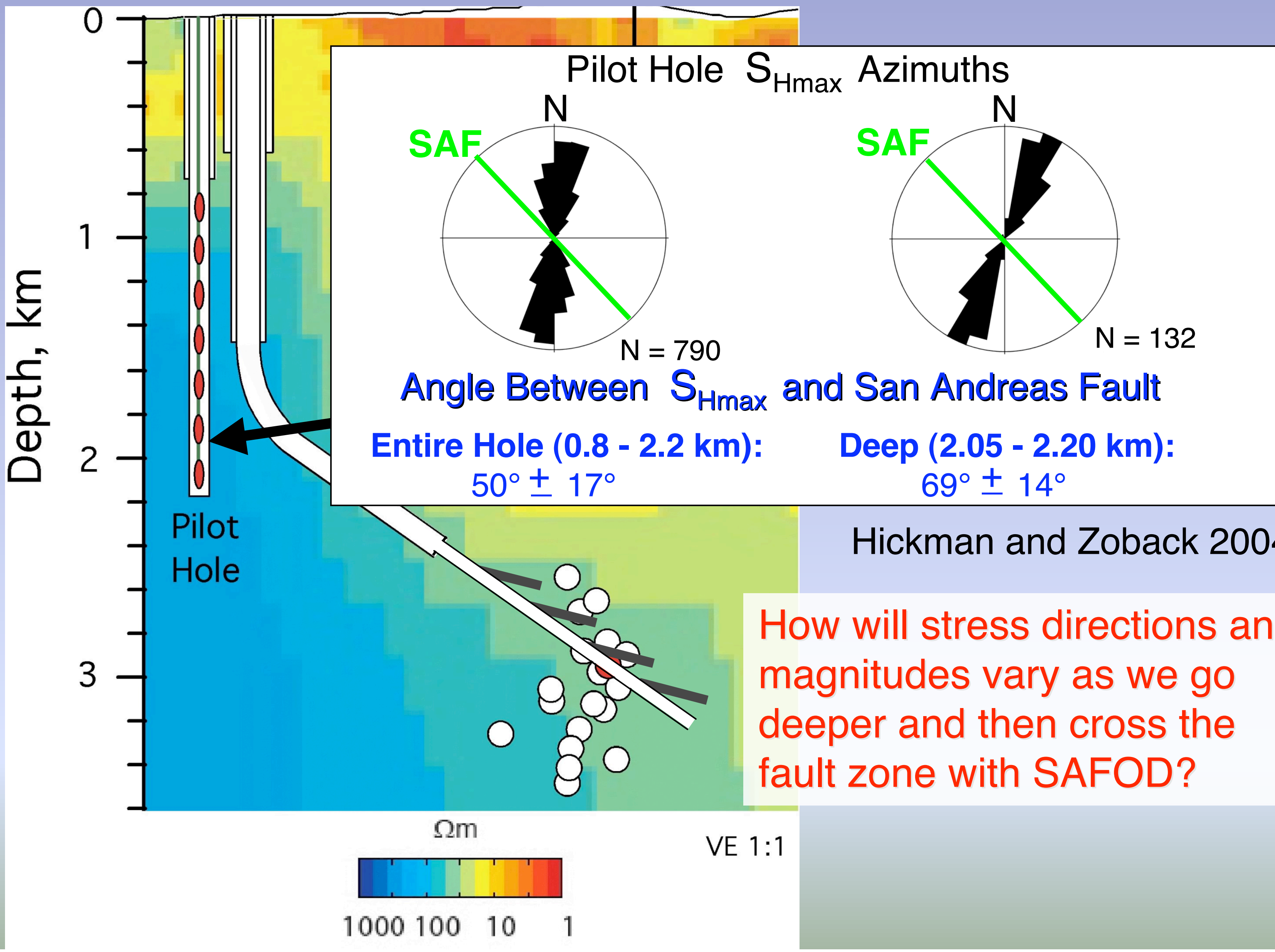
Dashed lines regional S_{Hmax} from modeling lithospheric buoyancy and plate interaction (Flesch et al, 2000)

- Heat flow and stress measurements led to Weak Fault/Strong Crust model.
- However, there are not many stress measurements close to the SAF.



Boness and Zoback 2004, Hickman and Zoback 2004

If the deepest S_{Hmax} orientation is representative of stresses at greater depth, then our observations are consistent with regional stress indicators and a strong crust/weak fault model (Chery et al., 2004).



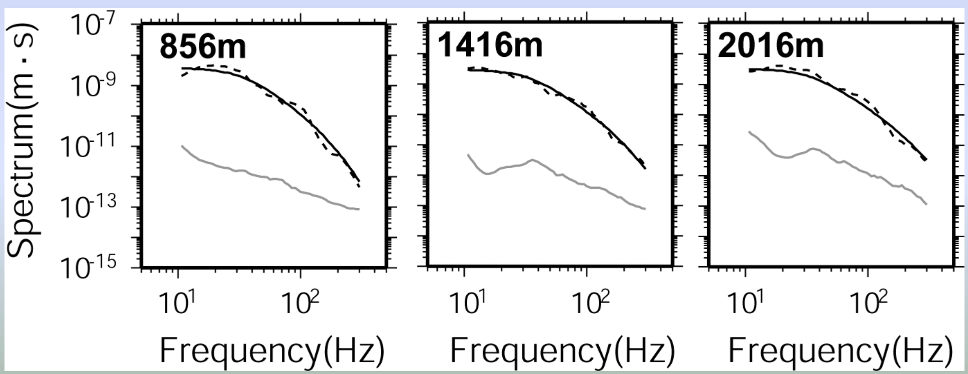
Hickman and Zoback 2004

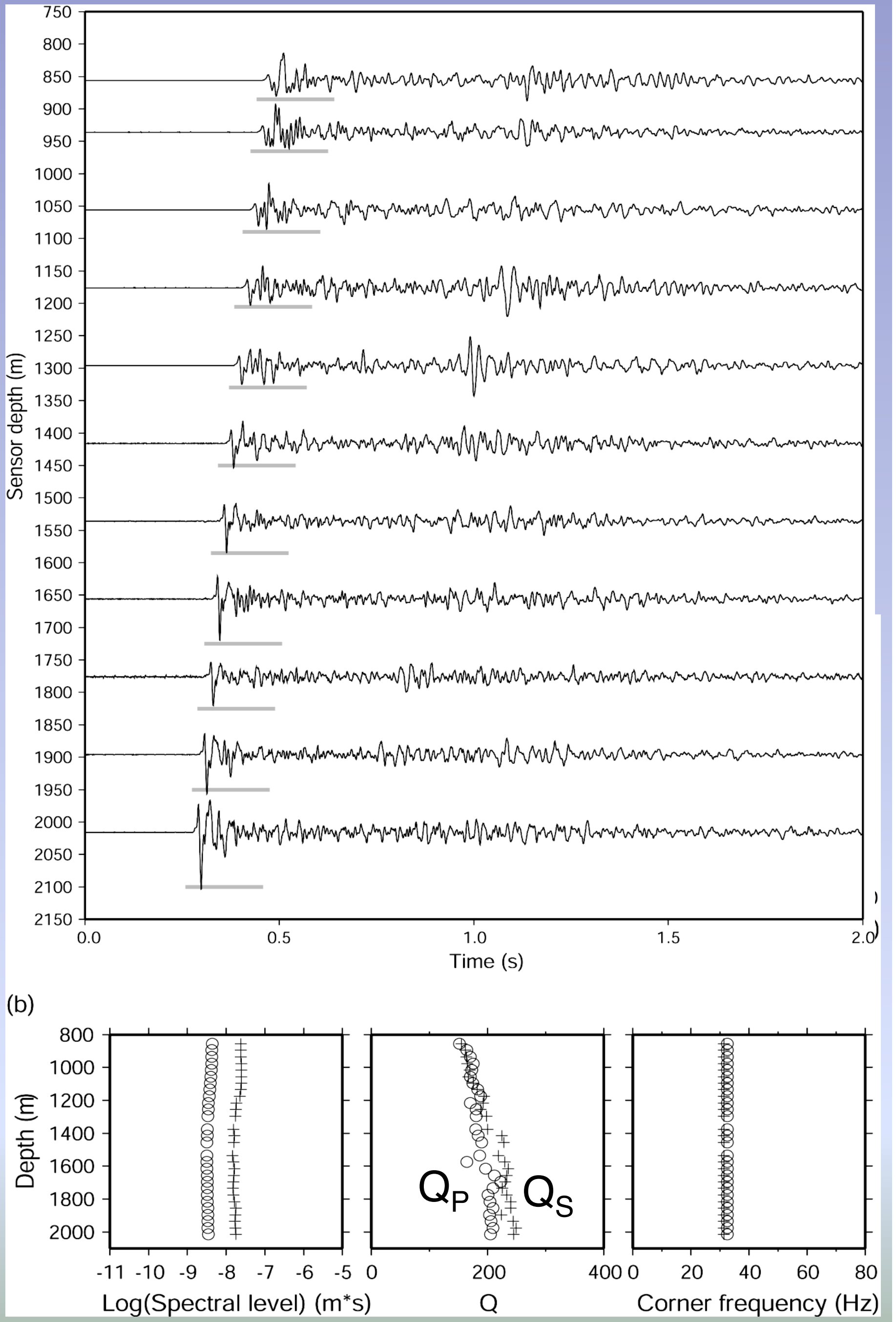
How will stress directions and magnitudes vary as we go deeper and then cross the fault zone with SAFOD?

Installing the Pilot Hole Seismic Array

Spectral Studies of Source Parameters
(Imanishi et al., 2004)

- Analysis of 32 levels of pilot hole array
- Measurement of seismic moment, corner frequencies (P&S) and Q (P&S)
- Target earthquake recorded (10/20/2004) at 2 km distance
  - Stress drop = 8.9 MPa
  - Source radius = 40 m
- Stress drop and source dimensions on the high side of global averages from deep borehole studies (Imanishi et al, in press)





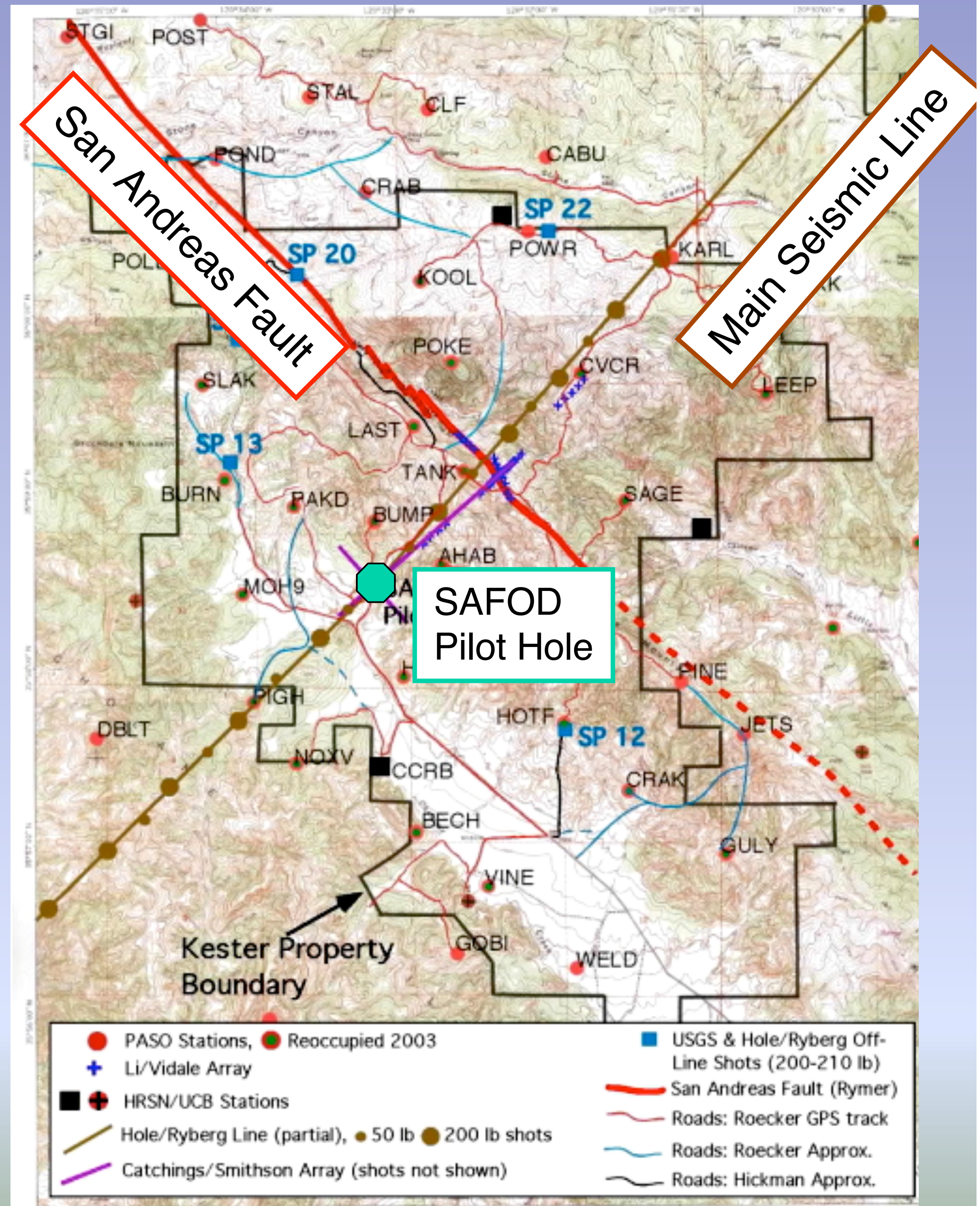
Oct./Nov. 2003 Seismic Experiments

Sources:
Hole/Ryberg shots (63@20-400 lbs)
Off-line shots (5@200 lbs)
Catchings auger holes (5 lbs)
Catchings shot guns

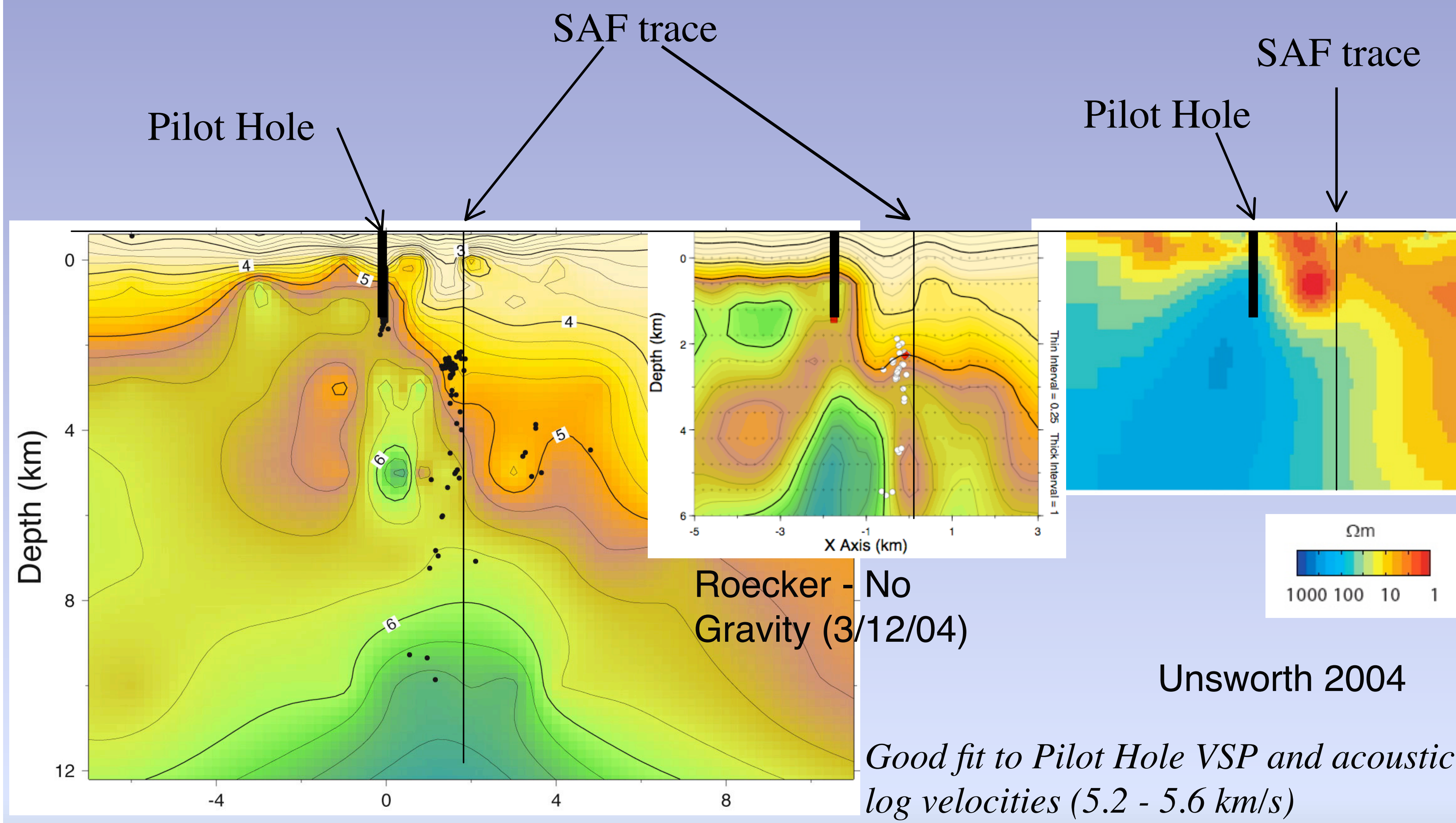
Temporary Arrays:
Thurber/Roecker array (PASO)
Hole/Ryberg line
Li/Vidale array
Catchings/Smithson
Malin array (Pilot Hole)
Ryberg off-line array

Permanent Networks:
N. Calif. Seismic Network (USGS)
High Res. Seismic Network (UCB)
UpSAR array (USGS)

Special Session at 2004 Fall AGU



Comparison of Seismic and Magnetotelluric Models

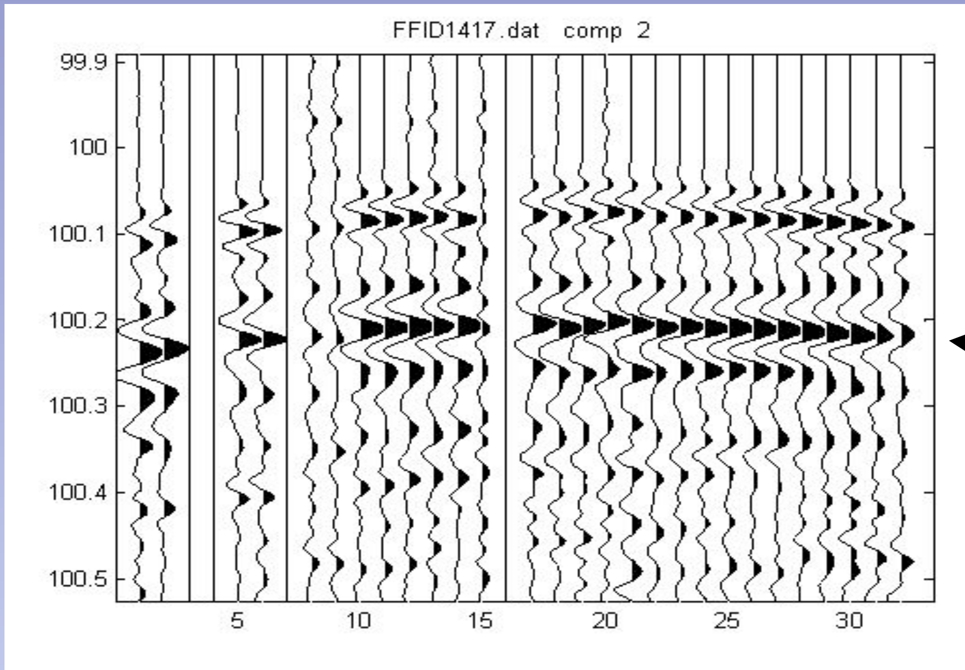


Thurber tomoADD (3/31/04)

Roecker - No Gravity (3/12/04)

Unsworth 2004

Good fit to Pilot Hole VSP and acoustic log velocities (5.2 - 5.6 km/s)

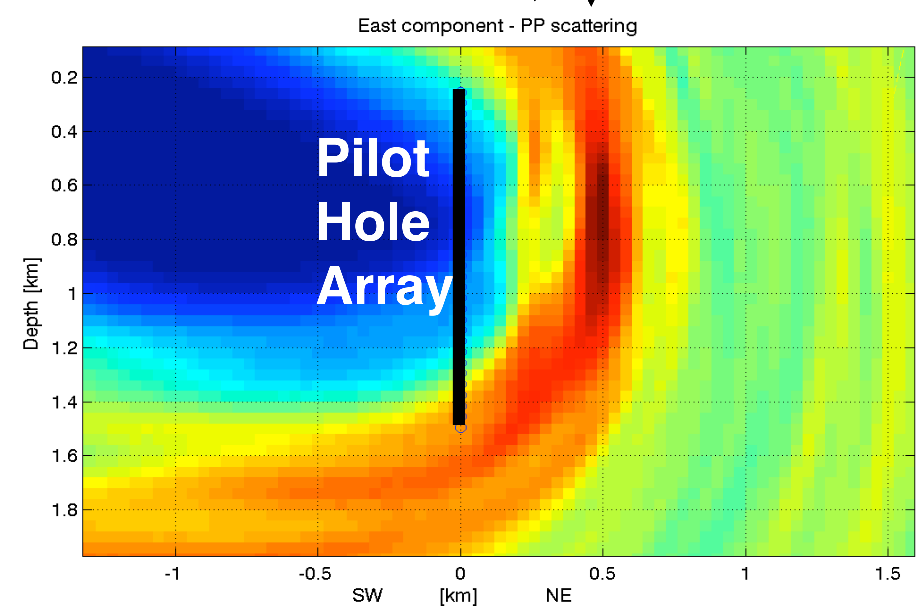


Pilot Hole Array: Radial component for shot detonated 2.90 km SW of Pilot Hole in Nov. 2003

Reflector

Faults

Three Shot Migration (shots 1402, 1417, 1406)

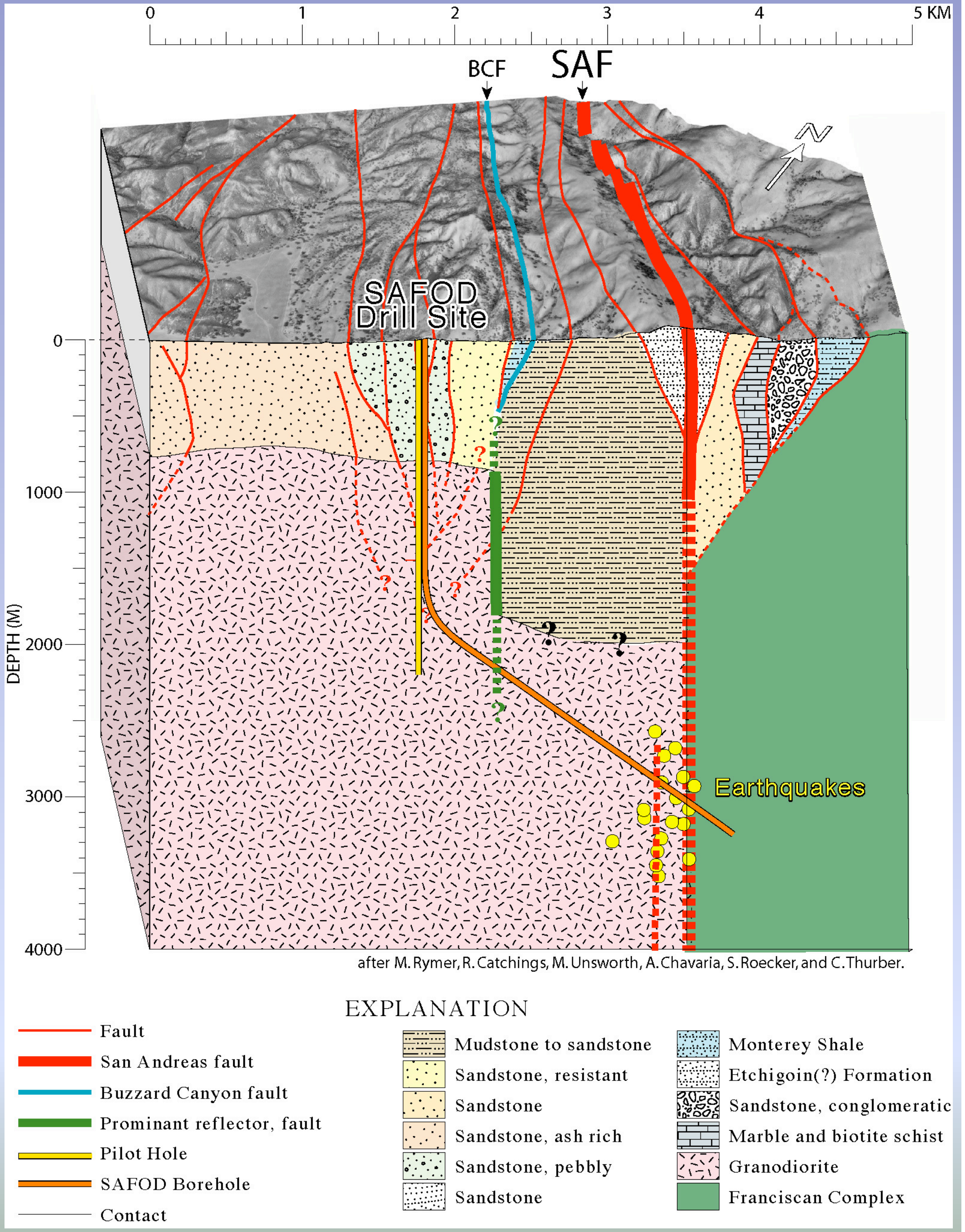


Andres Chavaria et al. 2004
(see also Chavaria et al. 2003)

Pre-Drilling Geological Model:

- Pilot Hole Results
- Active Source Seismic Surveys 1998, 2002, 2003
- Gravity and Magnetic Surveys
- Local seismic arrays (PASO, HRSN, NCSN)
- Surface Geologic Mapping

Model tested by SAFOD Phase 1 drilling



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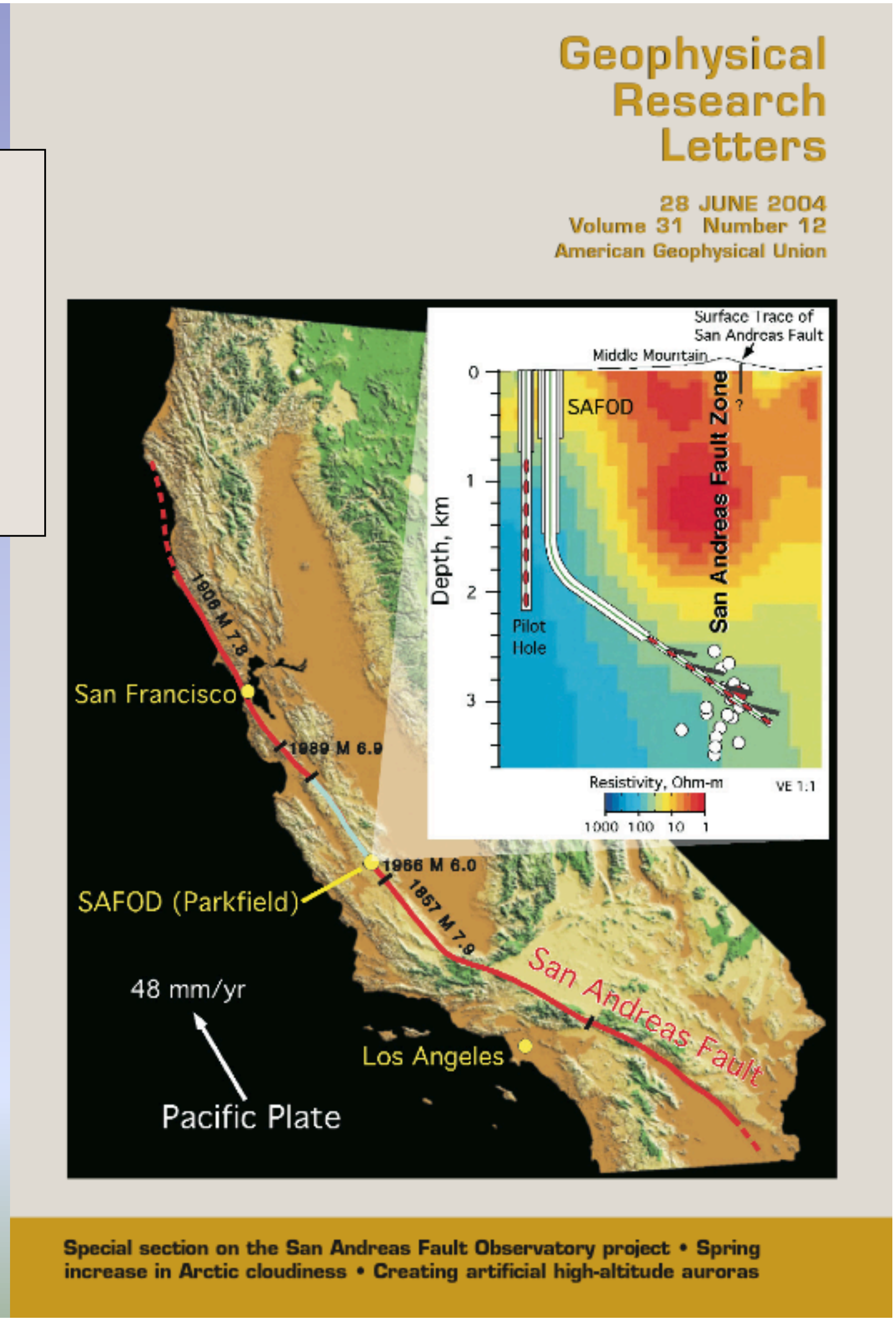
- PART 1: EARTHQUAKES AND CRUSTAL STRUCTURE, Vol. 31, No 12, 2004 (10 papers)
- PART 2: THERMOMECHANICAL SETTING, PHYSICAL PROPERTIES AND MINERALOGY, Vol. 31, No. 15, 2004 (10 papers)



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